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SCALING OF LARGE SPACE STRUCTURE JOINTS

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Various truss structures currently proposed for on-orbit assembly are too large to be tested on the ground. This has led to renewed interest in scale models for verification of predicted structural dynamic properties. However, a realistic scale model truss requires joints whose stiffness and damping properties are in-scale with those of the full-size counterpart.

This Phase I SBIR report describes the development and testing of a relatively simple, subscale model of an erectable truss joint which meets the requirements. It is a 1/5-scale version of a joint which, at full scale, connects 2-inch-diameter truss members of the type to be used in a large space structure now in development. Extensive test results are given to demonstrate that the model joint provides accurate, in-scale behavior. The primary conclusion is that accurate scale modeling of erectable trusses is quite feasible. ~~(cont.)~~ (JTS)

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19. The scaled joint is a key element for the construction of a dynamically-scaled model of a large truss. Such a model can serve as a testbed for a number of dynamic experiments and development programs. Of particular near-term interest is development of effective means for passive damping of truss structures.

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1. INTRODUCTION

Large orbiting spacecraft will often use trusses as primary, load-carrying structure. Favorable strength/weight and stiffness/weight ratios as well as compact stowage make trusses a natural candidate for erectable space structures. However the sheer size of proposed spacecraft raises important questions with respect to verification of their predicted dynamic properties. Assembled orbiting structures will be, in many cases, much too large for ground vibration testing. Some are not even capable of supporting their own weight in the earth's gravity. (Ø 1473)

This situation has led to renewed interest in scale models for structural dynamics. Finite element technology has, over the last two decades, largely replaced physical scale models for prediction of dynamic response. However, even the best mathematical models depend on a host of assumptions and must be verified by test. Scale models provide one of the few methods for even partial verification of the mathematical model of a large space structure at the fully assembled, system level.

While joint properties such as stiffness and damping are obviously important to overall system dynamics, the joints are invariably the most difficult parts of a truss to model, either mathematically by finite elements or physically via a scaled replica. This is true even when the joints behave essentially as linear elements. Complex geometries, compliance between contacting surfaces, friction, and other effects all make joint properties difficult to predict. Likewise, the problem of dimensional tolerances makes replica scale models of joints very costly at best.

The situations described above have led to a need for a low-cost, scale model truss joint with dynamic properties that are in-scale with a typical full-scale counterpart. The goal of the project described in this report was to develop and demonstrate such a scaled joint. It would facilitate a wide range of dynamic experiments involving scaled trusses.

The basic approach was to forgo replica scaling from the outset. In addition to its high cost, it was believed to be unnecessary. Since a well-designed truss has its members loaded primarily in tension/compression, the requirement for a scaled joint is simply that its axial stiffness and damping must be in-scale with the desired full-size prototype. The physical construction of the joint is immaterial as long as the stiffness and damping are correct. Also, for ground vibration tests, the joint need not have the quick-connect (astronaut-friendly) feature. The goal here was to develop and demonstrate at the component level a simple, low-cost scale joint which would accurately simulate the full-size joints currently proposed for space applications. Only erectable joints were considered since they seem to be favored over deployable types for very large structures.

This report documents the SBIR Phase I work on development of a scale model

joint. Following the Introduction and Objective, a short summary is given of the project activities, results, and conclusions. Section 4 summarizes some useful background on scaling laws for linear structural dynamics. Section 5 describes the candidate joint, a 1/5-scale item developed in cooperation with the NASA Dynamic Scale Model Technology (DSMT) project. Section 6 describes the test apparatus, instrumentation, and experimental method used to investigate the properties of the scaled joint. Section 7 gives the results of extensive testing. Finally, Section 8 gives the conclusions from Phase I work and outlines the direction for continuing effort.

2. OBJECTIVE

The Phase I objective of this SBIR program was to produce a low-cost, scaled truss joint suitable for use in dynamically-scaled models of large space structures.

3. SUMMARY

The objective was achieved. A joint, hereinafter referred to as the Able joint after its designer (AEC-Able Engineering, Goleta, CA) was found which had stiffness properties close to the desired value. With minor modifications, the stiffness was essentially on target. Damping was found to be similar to that observed in full-scale joints; i.e., almost too small to measure by direct means.

Two sources were used to establish full-scale target properties. The first was tests performed previously by CSA Engineering on a full-scale erectable joint. Designated as the Wendell or Star-Net joint, it is a candidate for the primary truss structure of a large space system now in development.[1]

The second source, which became available after the start of this project, was a calculated joint stiffness obtained from NASA/LaRC.[2] It was higher than the measured value for the Star-Net joint but was considered by NASA to be representative of the state-of-the-art. It had been chosen as the target stiffness for scaled joints in a parallel NASA program, called the Pathfinder project. That program's goal is the development of a distorted-scale model of a very large space structure.

The higher stiffness value from NASA was eventually accepted as the more realistic target. It is 94,400 lbf/inch for a 3.10-inch joint length (both values referred to 1/5 scale) which implies a compliance per unit length of 3.42×10^{-6} lbf^{-1}.

Originally, it had been planned to use finite element modeling for preliminary design of the scaled joint. It was expected that this would lead to a first prototype joint having approximately the correct stiffness which would then be tuned empirically to obtain the desired value. In a fortunate coincidence, CSA became involved in the NASA Pathfinder project and thereby gained access to a wealth of experimental data which rendered the analytical design unnecessary.

The final result was a relatively simple, 1/5-scale model of a joint designed to connect 2-inch-diameter truss members. As a bonus, it has the quick-connect feature which, while not essential, is highly convenient for assembling ground test articles. Current NASA plans are to have the joint manufactured in fairly large quantities for the Pathfinder model. This should make it available at low cost for Air Force applications, at least during a certain time window.

Stiffness of the original 1/5-scale Able joint, averaged over several joints and a range of load levels and frequencies, was found to be 93,900 lbf/inch with a standard deviation of 3,100 lbf/inch. Joint length at 1/5-scale was 4.1 inches. Compliance per unit length was therefore 2.60×10^{-6} lbf^{-1}, about 20% below the

[1] Kienholz, D.A. and Allen, B.R., "Force-State Testing of a Quick-Connect Joint," CSA Engineering Report 87-02-01, February, 1987.

[2] Gronet, M.R., "COFS III Pathfinder Phase Interim Review," Lockheed Missiles and Space Co., Sunnyvale, CA, September 28, 1987.

target. Damping, specified in terms of structural loss factor, varied randomly in the range of 0.002 to 0.007. The joint design was reviewed and, by minor modifications, the compliance per unit length was increased to within about 5% of the target value. Damping was unchanged by the modifications.

Primary conclusions from the project to date are as follows.

1. The Able joint should satisfy the requirement for a low-cost, dynamically scaled joint.
2. When properly assembled, the subscale Able joint, like the full scale Star-Net joint, is essentially a linear structural element with negligible damping.
3. Stiffness of the Able joint, as originally designed, is slightly higher than the target value, although the latter is itself somewhat arbitrary. Joint stiffness can be reduced if desired by minor modifications.
4. Stiffness of the 1/5 scale Able joint is roughly equal to that of an equal length of the aluminum truss tubing to which it mates.
5. The linearity, low damping, and stiffness properties of joints tested to date, either full or subscale, suggest that dynamic properties of erectable trusses will not be dominated by the joints, or at least not to the extent previously expected. Disregarding the added mass of the joints, dynamic behavior will be essentially the same as if the tubes were simply extended to a common point and welded together.

It is recommended that continuing work should now concentrate on the next level: fabrication and testing of a scale model truss for use in dynamic experiments. In particular, the scale truss should be used to attack the problem of designing passive damping into truss structures. It is now clear that dissipation in joints, usually considered to be the primary damping mechanism, is far too weak to provide adequate damping for global truss modes. The scaled truss should also be generic in that it could be easily reconfigured for a variety of experiments, including those where selected truss members are replaced by actuators.

4. DYNAMIC SCALING

The replica scaling laws for linear structural dynamics are quite simple, particularly when the model is constructed of the same material as the full-scale prototype. The relationships for various physical quantities are given in Table 1.

$$\lambda = \frac{\text{model length}}{\text{prototype length}}$$

Quantity	$\frac{\text{model value}}{\text{prototype value}}$
Length	λ
Mass	λ^3
Time	λ
Displacement	λ
Area	λ^2
Volume	λ^3
Velocity	1
Acceleration	$1/\lambda$
Force	λ^2
Stress	1
Frequency	$1/\lambda$
Damping	1
Moment of inertia	λ^5
Torque	λ^3

Table 1. Scaling relationships for replica models

Of primary interest here are the ratios for stiffness, damping, and force. Stiffness scales with length to the first power. Thus a 1/5-scale joint must be 1/5 as stiff as its full-scale counterpart. Damping is inherently dimensionless and scales independent of length. Force scales with length squared. Thus a test of a 1/5-scale joint will require only 1/25th the force of a full-scale test. Since the target full-scale joints are designed for loads on the order of 1000 lbf, a 40-lbf dynamic exciter was adequate for testing the scaled versions.

An interesting and highly useful concept for dynamic scaling of truss structures is that of distorted scaling. [3] It may be shown that the global vibration modes of a truss with lumped masses can be reproduced by a scale model even if the length scale for overall dimensions such as truss bay length differs from the length scale for feature dimensions such as member diameter and joint size.

The importance of this is obvious if one considers the upper and lower limits on scale factor when a large truss is to be modeled. The length scale (model length/prototype length) must be small enough such that the model will fit in the available test facility. However, the scale factor must be large enough such that details and features such as joints are not reduced to the point where they are difficult to manufacture and handle. For a model of a large truss structure, there may be no single scale factor that satisfies both criteria.

The Pathfinder project provides an excellent example. The 800-foot overall length of the full-scale target structure is scaled by a factor of 0.1 to fit into a test bay approximately 90 feet long. The two-inch tube diameters and joint dimensions are scaled by a factor of 0.2, about optimum for manufacturing cost and handling. Sample joints and tubes were built at one-tenth scale but were fragile, difficult to handle, and prohibitively expensive. Without distorted scaling, the entire project would have been impossible.

[3] Letchworth, R., Gronet, M.J., and Crawley, E.F., "Conceptual Design of a Space Station Dynamic Scale Model," Second NASA/DoD Control Structure Interaction Technology Conference, Colorado Springs, CO, November, 1987.

5. JOINT DESIGN

Figure 1 shows a diagram of the 1/5-scale Able joint. Like most erectable joint designs, it is based on a central aluminum node ball with a number of threaded radial holes. Each truss member connects through a quick-connect coupling to a standoff which threads into the ball. The mushroom-shaped screw head in the end of the truss member slides into a mating slot in the standoff. It is captured by the internally-threaded collar which bears against the standoff. After assembly, the shank of the mushroom head is loaded in tension and the collar is in compression. Attractive features of the joint include its ease of assembly, inherent simplicity, and lack of clos olerances.

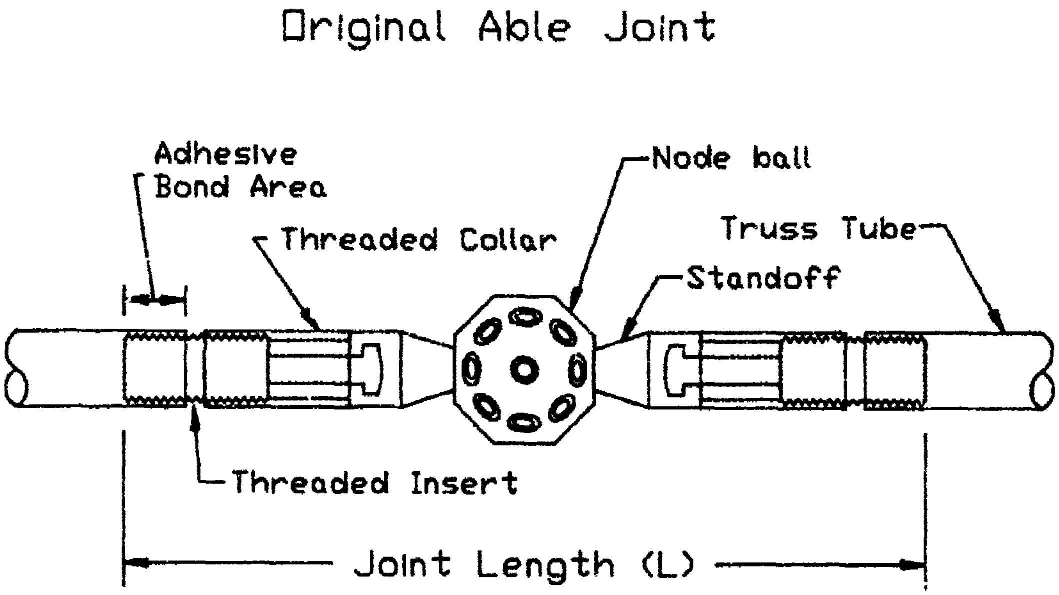


Figure 1. 1/5-Scale Able joint

Full-scale versions of the joint have a spring-loaded ratcheting mechanism which allows an astronaut to spin the collar tight by simply releasing a trigger. This feature, unnecessary for ground testing, was eventually deleted from the 1/5-scale version although it was present in the examples tested for this project. It was determined by test that an assembly torque of 6 in-lbf on the collar was sufficient to eliminate nonlinearity in the joint. From Table 1, this corresponds to 62 ft-lbf for a full scale joint. Since this value was considered reasonable for full-scale assembly, the 1/5-scale versions were assembled at 6 in-lbf for stiffness and damping tests.

6. TEST APPARATUS AND METHOD

6.1 Test Apparatus

Figures 2 and 3 show the apparatus used for testing the 1/5-scale joints. One end of the joint is fixed to a rigid ground through a strain-gage load cell. A controlled force is applied to the other end by means of an electrodynamic shaker. The pushrod connecting the shaker to one end of the joint is restrained against lateral motion by a linear bearing on a rigid support.

Figures 4 and 5 show details of the sensors and fixturing. The smaller diameter tubes on either side of the joint are witness tubes which form an extensometer. Each witness tube is held in a triple clamp to the joint tube on the right side of the joint in Figure 4. The left end of each witness tube is supported off the left joint tube only by thin flexures which restrain it laterally but add no significant axial stiffness. Relative axial displacement between the sensor bracket on the left of the joint and the left end of each witness tube is sensed by a noncontacting eddy current probe. Signals from the two sensors are added to obtain true axial deflection, even in the presence of bending caused by slight eccentricities in the load path.

A similar fixturing arrangement is used with linear velocity transducers (LVT's) which sense relative velocity across the joint (Figure 4). These are used only when measuring the overall force-state map of the joint. For more precise measurements of stiffness and damping, the LVT's are removed to eliminate the small residual friction between the probe and transducer body. This effect, negligible when testing full scale joints, was found to produce significant error in damping measurements for 1/5-scale versions.

6.2 Data Processing

Figure 6 shows the data system for joint testing. Analog signals from the force, displacement, and velocity transducers are digitized and stored on disk. Force waveforms can be sinusoidal, amplitude-modulated sinusoidal, random, or burst random. Displays can be force-deflection plots (hysteresis loops), complex stiffness (ratio of Fourier transforms of force and deflection), or force-state maps (3-dimensional plots of force versus displacement and velocity).

Generally, force state maps are most useful for characterizing strong nonlinearities. They were used in the current project only for investigating the effects of assembly torque. Simple force-deflection plots were the preferred method for determining stiffness and for characterizing weak nonlinearities. Several methods were tried for measurement of damping. The method selected was to infer the structural loss factor from the phase angle of a complex stiffness measurement made using

either sine or random input. Sine was preferred because it gave somewhat better repeatability.

Figure 4 shows that the test section includes not only the joint but also a short length of truss tubing on either side of it. The measured compliance of this series combination is greater than that of the joint alone. The compliance of the aluminum tube, 0.400 inches in outside diameter and 0.021 inches in wall thickness, was calculated and subtracted from each raw measurement to arrive at a compliance for the joint alone. Implicit in this method is a working definition for "joint." It is everything inside the test section that is not uniform annular tubing. The length of the Able joint is therefore 4.1 inches, slightly greater than the distance between the truss tube ends (Figure 1).

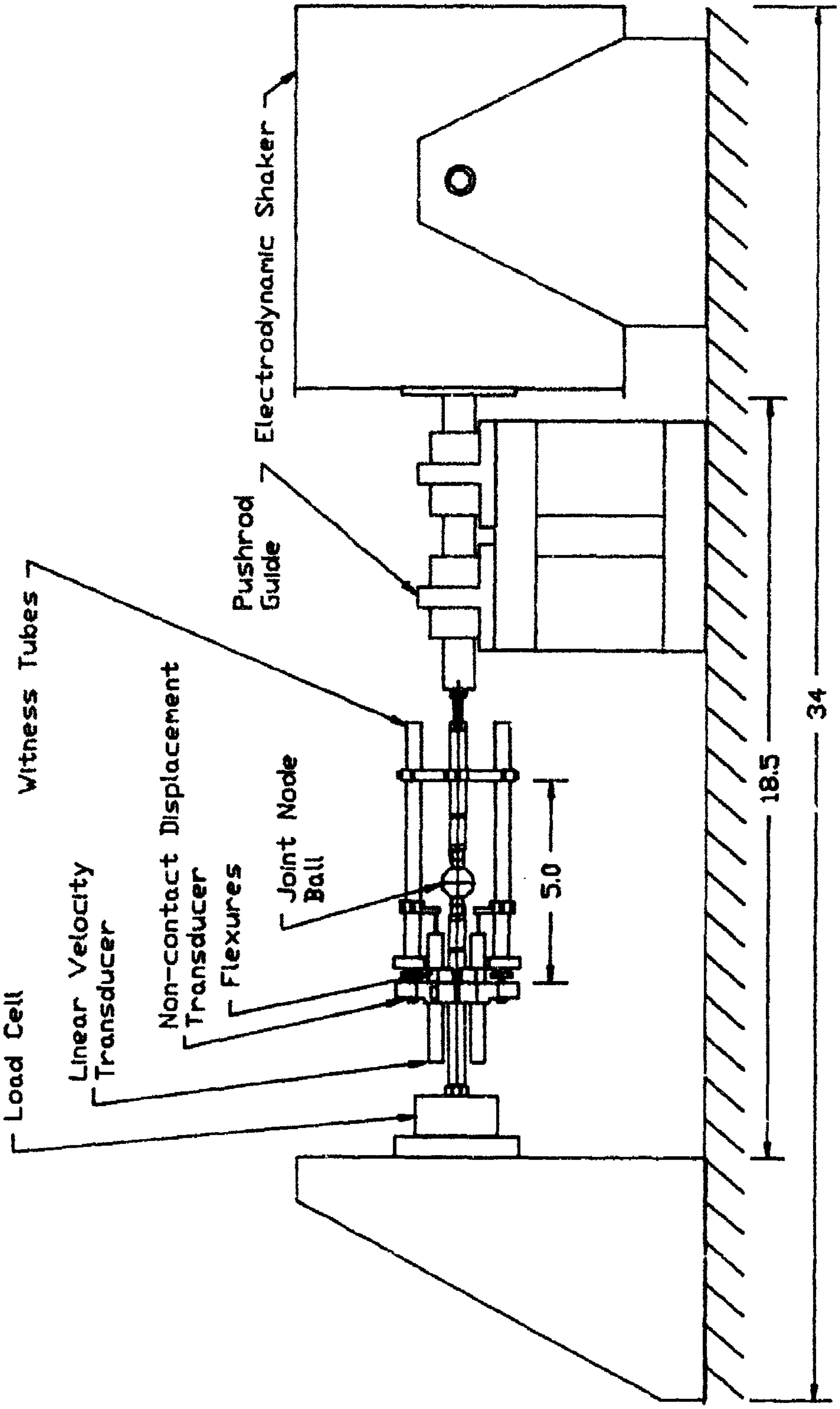


Figure 2. Apparatus for testing of a 1/5-scale truss joint

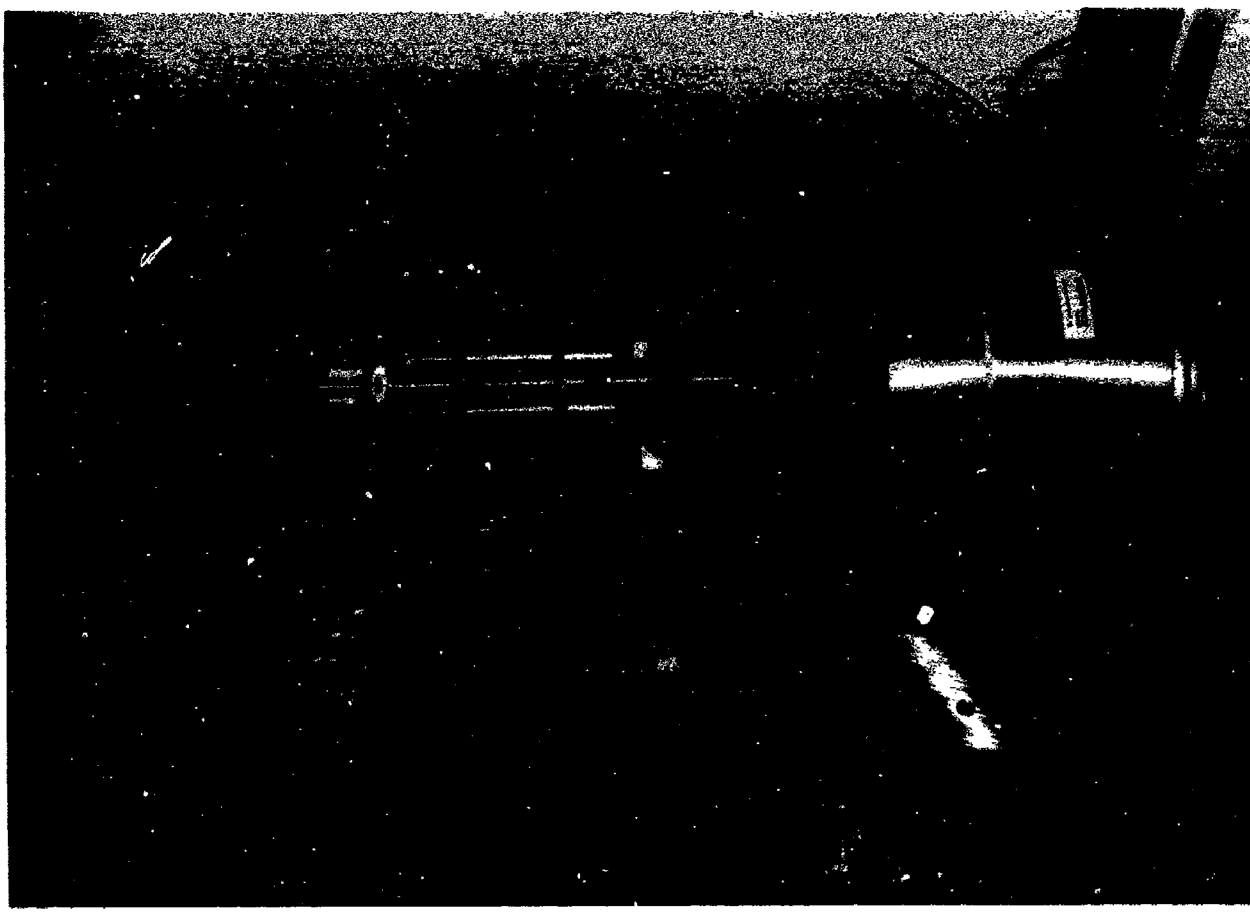


Figure 3. Photograph of test apparatus

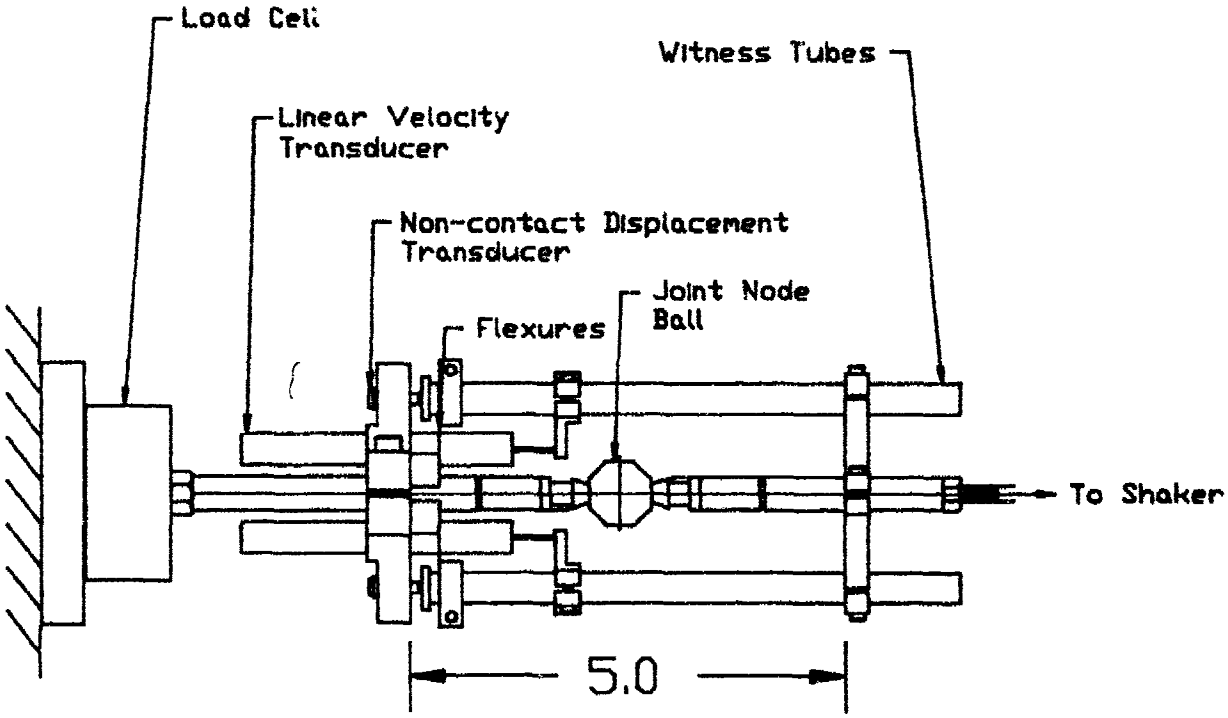


Figure 4. Sensor and fixturing details

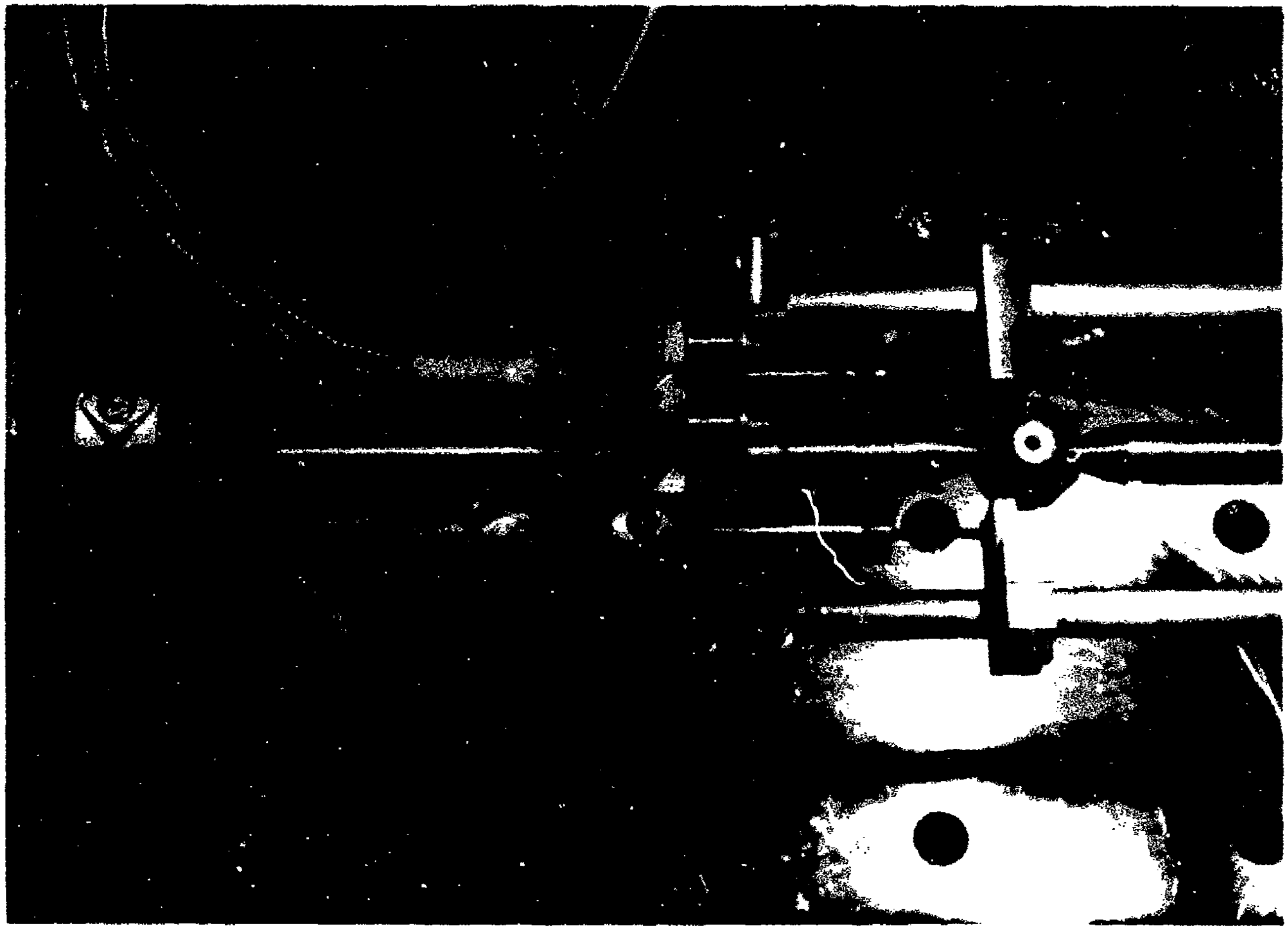


Figure 5. Photograph of sensors and fixturing

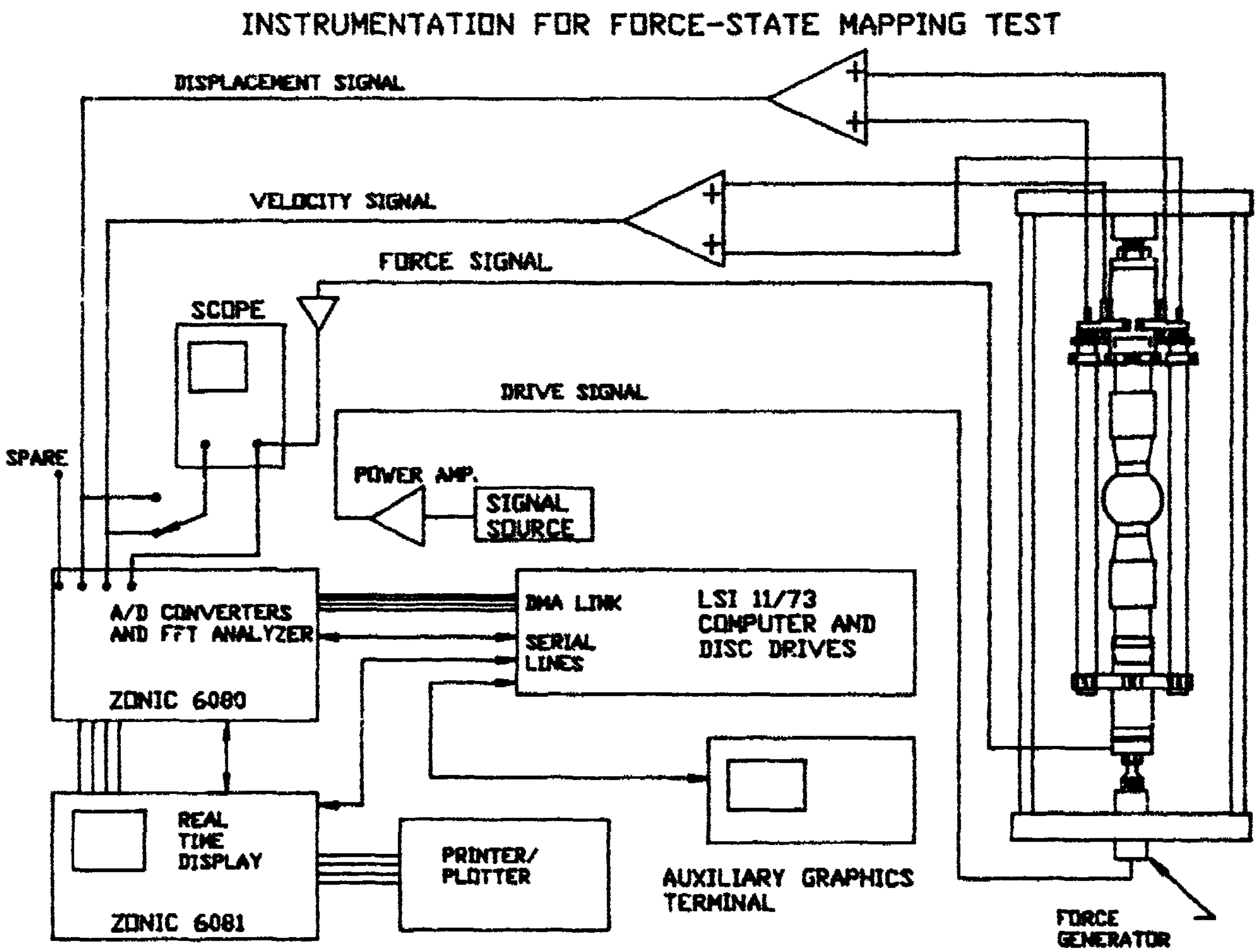


Figure 6. Instrumentation for joint testing

7. TEST RESULTS

This section gives the results of tests performed to characterize the candidate 1/5-scale joint design. The tests were of the following types.

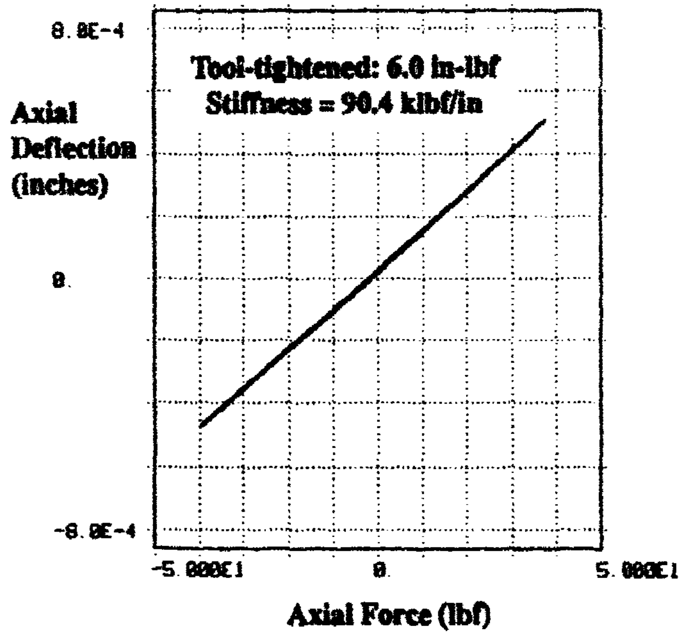
1. **Assembly tightness tests.** These identified the assembly torque required to provide essentially linear behavior.
2. **Force-state mapping tests.** These verified the linear behavior and provided a graphic representation of the nature of nonlinearity when assembly torque is inadequate.
3. **Complex stiffness tests.** These tests, the most important of the series, provided stiffness and damping values for the joint at various values of load and frequency.
4. **Aging test.** This high-cycle, low-load test verified that no appreciable change in joint properties would occur over the expected life of a model.

A full set of tests was performed on the baseline Able joint. Following data analysis, it was clear that the stiffness of the original design was somewhat above the target. Minor modifications were performed to reduce the stiffness and an abbreviated set of tests was performed to verify that this "tuning" process had been successful. Sections 7.1 through 7.4 give results for the baseline joints and Section 7.5 gives results for the modified version.

7.1 Assembly Tightness Tests

Figure 7 shows typical force-deflection plots for a baseline joint under two conditions. The upper plot shows results when the joints are spring-tight; i.e., the collars are tightened only by their internal springs. Torque for this situation is too small to measure accurately but is certainly less than 0.5 in-lbf. The lower plot shows the result when the collars are tightened to 6.0 in-lbf. Inadequate assembly torque produces a pronounced softening nonlinearity in tension which disappears when the collars are tightened. Additional tests showed no advantage in using an assembly torque greater than 6.0 in-lbf; no further increase in stiffness occurred. As noted earlier, the stiffness values given with each plot are for the joint only. The effect of the 0.9-inch length of truss tube within the 5.0-inch test section has been removed analytically.

Table 2 summarizes results of assembly tightness tests on a number of joints and at different load levels. Stiffness values in every case are for the joint only and were obtained from force-deflection plots with sine excitation at 1.0 Hz.



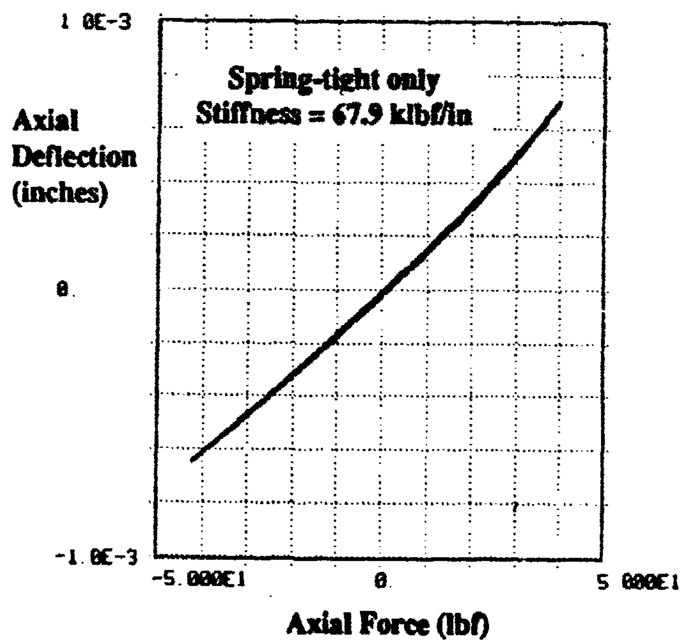


Figure 7. Force-deflection plots for two values of assembly torque. Test section length = 5.0 inches. Measured stiffness is corrected to 4.1-inch joint length (see text).

Joint Stiffness in klbf/in

Torque (in-lbf)	Load (lbf)	2	8	40
0.0 (spring-tight)	Joint 1	59.6	58.7	67.9
	Joint 2			66.8
	Joint 3			72.8
3.0 (tool-tightened)	Joint 1	86.6	87.6	86.0
	Joint 2			92.5
	Joint 3			92.5
6.0 (tool-tightened)	Joint 1	92.0	92.7	90.4
	Joint 2			93.9
	Joint 3			98.2

all tests at 1.0 Hz

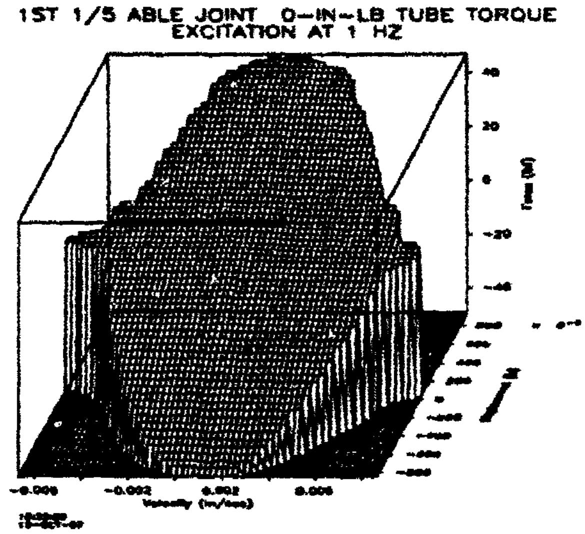
Table 2. Effect of assembly torque on joint stiffness

Conclusions from the tightness tests are as follows.

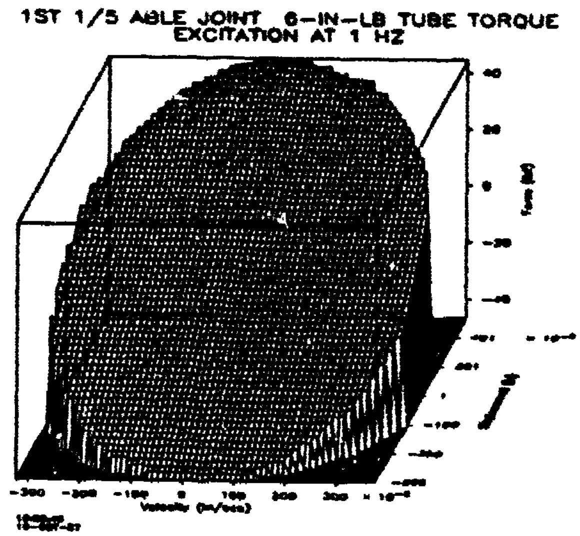
1. The joints are quite linear when properly tightened.
2. The optimum assembly torque is 6.0 in-lbf.
3. Spring-loaded tighteners inside the collars are unnecessary since they do not produce enough tightening torque to linearize the joints.

7.2 Force-State Mapping Tests

Figure 8 shows force-state maps for a joint at two levels of tightening torque, as explained in the previous section. These were obtained using an amplitude-modulated sine signal as the force input. The nonlinearity at low torque is visible primarily in terms of the outline of the contour plot. It was found that generally, force-state maps, while useful for characterizing strong nonlinearity, do not show sufficient detail to be useful in examining the relatively mild effects which occur in erectable joints.



Spring-Tight



Tool-Tightened
(6 in-lbf)

Figure 8. Force state maps for spring-tight and tool-tightened joints

7.3 Complex Stiffness Tests

The main set of tests was run using an assembly torque of 6.0 in-lbf. Figure 9 shows an expanded view of a typical force-deflection plot measured with sine input at 1.0 Hz and peak load of approximately 40 lbf. The slope of the line indicates a stiffness within the test section of 72,700 lbf/inch which corrects to 90,400 lbf/inch for the joint alone. The negligible damping of the joint is evidenced by the fact that the hysteresis "loop" has collapsed almost to a single line.

Table 3 summarizes stiffness result for three examples of the 1/5-scale Able joints, tested over a range of loads and frequencies. The scatter is quite small (standard error = 3.3%) and there is no clear trend with either force level or frequency.

Stiffness in klbf/in

Freq (Hz)	Load (lbf)	2	8	40
1.0	Joint 1	92.0	92.7	90.4
	Joint 2	91.3	90.7	93.2
	Joint 3	91.2	97.9	96.4
5.0	Joint 1	91.2	92.4	91.1
	Joint 2	92.0	94.9	94.4
	Joint 3	98.4	98.7	99.1
25.	Joint 1	89.6	91.3	91.6
	Joint 2	90.8	95.2	95.9
	Joint 3	96.7	98.7	98.0

Table 3. Results of joint stiffness tests

Figure 10 shows the relationship of the actual stiffness to the target stiffness. The upper plot shows force-deflection lines corresponding to the actual joint when spring-tight as well as tool-tightened. The latter corresponds quite closely to the target value. The lower plot shows the relationship of actual and target stiffnesses for a strut assembly; i.e., a truss member tube with half a joint on either end. Two conclusions may be drawn.

1. The joints are quite close to their target stiffness.
2. A given level of error in joint stiffness (relative to target) will produce a much smaller error in the overall strut stiffness. This occurs simply because the truss member is much longer than the joint and therefore tends to dominate the strut compliance.

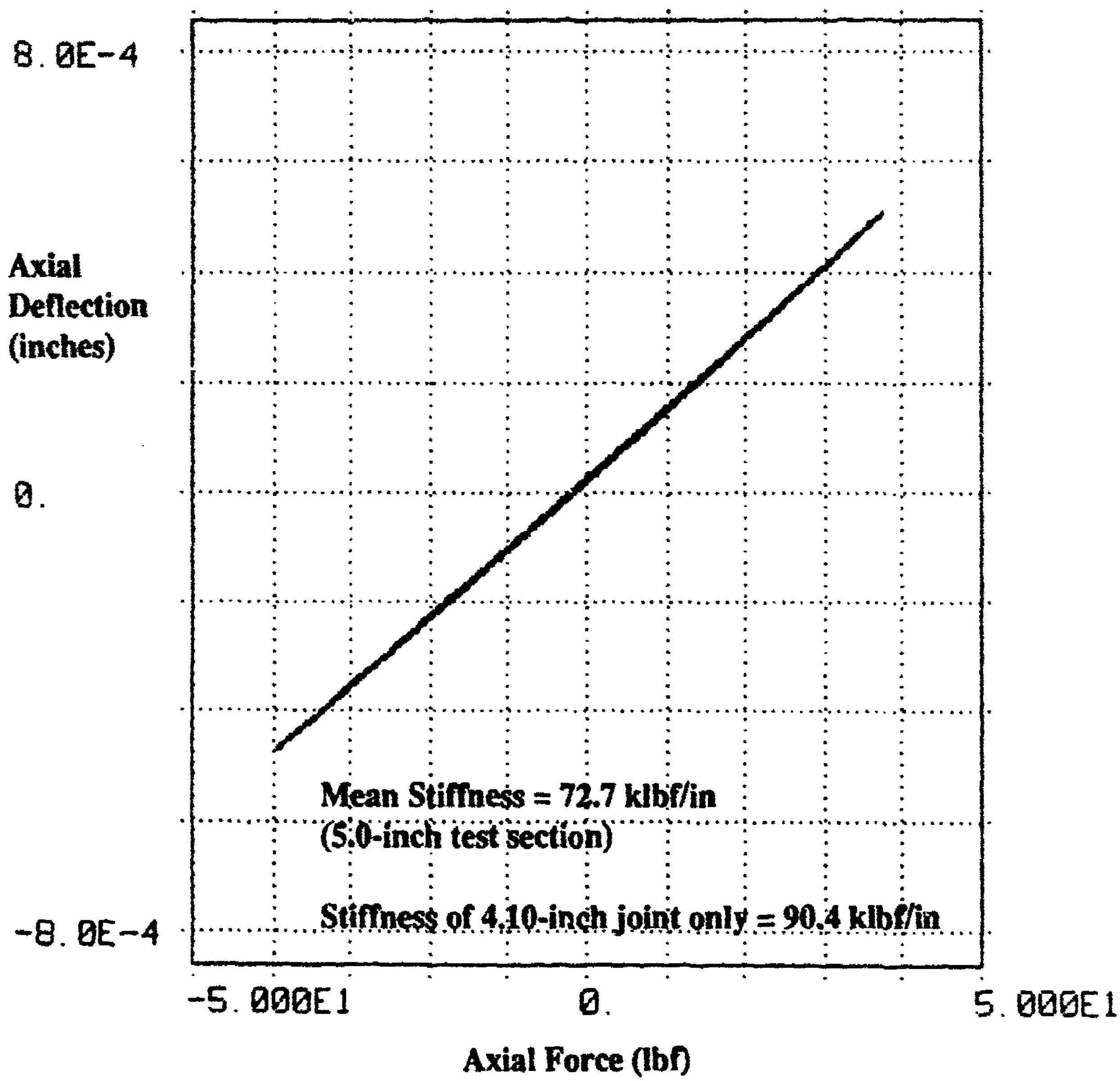
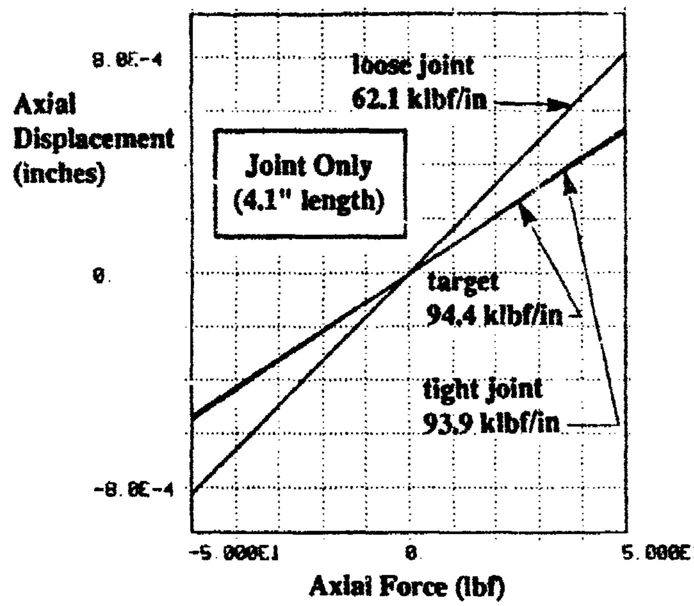


Figure 9. Typical force-deflection plot. (1.0 Hz input).



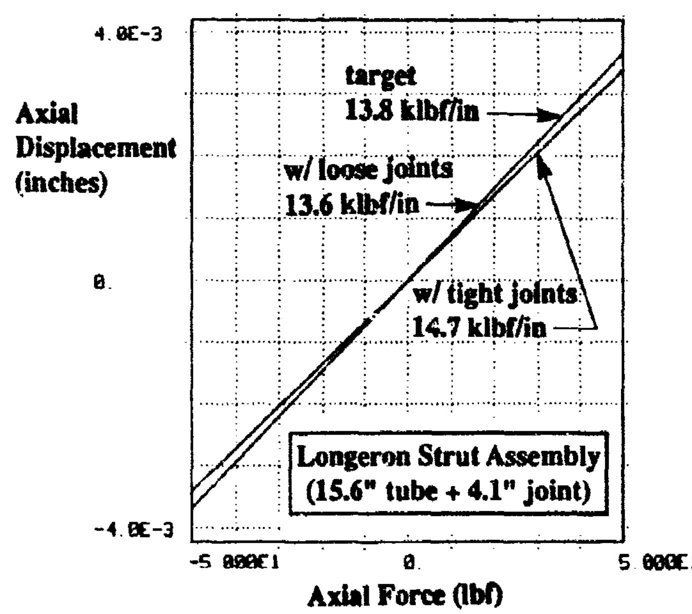


Figure 10. Measured versus target stiffness for joint only and for strut assembly

Loss Factor η

Freq (Hz) \ Load (lbf)		2	8	40
1.0	Joint 1			
	Joint 2	.0069	.0044	.0056
	Joint 3	.0025	.0044	.0051
5.0	Joint 1	.0027	.0019	.0051
	Joint 2	.0025	.0021	.0032
	Joint 3	.0049	.0039	.0032
25.0	Joint 1	.0041	.0047	.0062
	Joint 2	.0054	.0051	.0057
	Joint 3	.0062	.0049	.0058

Table 4. Results of joint damping tests

Damping test results are summarized in Table 4. Loss factor for the joint was difficult to measure because, in every case, the value was essentially at the threshold of resolution for measurement by the direct complex stiffness method. Scatter was high with a standard error of about 30%. This was expected given the very small damping levels. The difficulty could have been overcome by designing an indirect (resonant) test but this was considered unnecessary. The main conclusion is obvious; damping in the joints is very small. This is exactly the situation found previously in testing of the full-scale Star-Net joint. Modal loss factors for an entire truss will be several times smaller than the values in Table 4 because most of the modal strain energy is in the truss members, rather than the joints.

The overall conclusion is simply that erectable truss joints of the types now proposed are ineffective as dampers. Given the need for damping in vibration control and stability of large space structures, it is clear that other means must be found.

7.4 Aging Tests

An accelerated aging test was conducted to determine if properties of the scale joint would change significantly with age. Stiffness measurements were made on a joint before and after 10^7 cycles at a load level of 2 lbf. The driving frequency was 100 Hz: high enough to complete the test in a reasonable time but low enough to avoid fixture resonances.

Joint Stiffness in klbf/in

Aging	Load (lbf) / Freq (Hz)	2.0	8.0	40.
Before	1.0	91.3	90.7	93.2
	25.0	90.8	95.2	95.9
After	1.0	93.9	91.9	96.7
	25.0	95.8	96.1	94.8

Table 5. Results of joint aging tests

Table 5 shows results of the before-and-after stiffness tests. No significant change was found. The conclusion was that, at least for the small loads imposed during ground vibration tests, aging will not be a problem.

7.5 Tests of Modified Joints

The baseline Able joints showed a mean stiffness of 93,900 lbf/inch for a joint length of 4.10 inch. This implies a compliance per unit length of 2.60 x 10^{-6} lbf^{-1}, about 20% below the target (i.e., stiffness was too high). While this was considered fairly close given the somewhat arbitrary nature of the target, a project goal was to demonstrate that a preselected stiffness could be obtained. The design of the Able joint was therefore reviewed to identify changes that could reduce its stiffness slightly. Figure 11 shows the result. These changes were implemented on one joint and it was retested. Results are shown in Table 6. Compliance per unit length for the modified joint was within 5% of the target value.

The conclusion was that the desired stiffness could, in fact be obtained. While the original joint design may actually be preferrable for construction of a scale truss, it has been demonstrated that its stiffness can be tuned, at least over a moderate range.

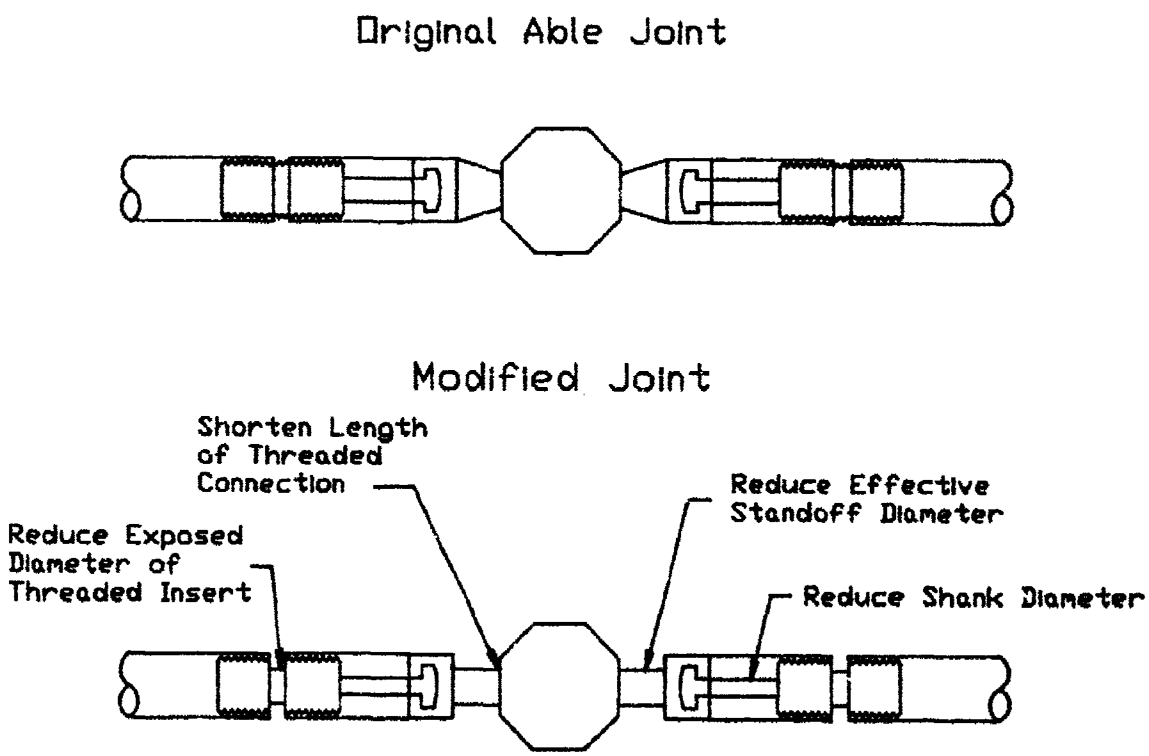


Figure 11. Modifications to Able joint to adjust stiffness

Configuration	Stiffness K klbf/in	Length L inches	$\frac{\text{Compliance}}{\text{Length}}$ $\frac{1}{KL}$ lbf $^{-1}$
Baseline	93.9	4.1	2.58×10^{-6}
Modified: Reduced diameters of • Standoff • Screw Shank • Threaded Insert	67.7	4.1	3.60×10^{-6}
Modified as above plus shortened threaded connector to node ball	65.1	4.1	3.75×10^{-6}

Table 6. Stiffness of modified Able joint (target value for $1/KL$ is 3.42×10^{-6} lbf^{-1})

8. CONCLUSIONS

Overall conclusions from the project are as follows.

1. A simple, practical scale joint has been demonstrated which has stiffness in-scale with joints currently proposed for large space structure.
2. Like its full-scale counterparts, the Able joint is essentially linear with negligible damping.
3. Stiffness of the joint is roughly equal to that of an equal length of the aluminum tube to which it mates. Truss properties will not be joint-dominated to the extent previously expected.
4. The joints should be available at reasonable cost due to their quantity production for a parallel NASA program.
5. Energy dissipation in erectable joints will be only a very weak damping mechanism

The work reported here was an important step towards the ultimate goal of producing a dynamically scaled model of a large truss structure. This would serve as a testbed for any number of dynamic experiments and development programs. The natural direction for continuing work at this point is to actually produce such a testbed.

As noted earlier, an immediate use for a scaled truss would be development of advanced techniques for passive damping. This work has shown clearly that erectable joints of the types currently proposed have very little inherent damping. Specialized development will be required to exploit the joints as dampers.